Acoustic Tomography of Natural Bubble Fields and Ship Wakes

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LONG-TERM GOALS

The primary long-range objectives are the development and the refinement of algorithms for acoustic tomography with applications to quantitative measurement of bubble fields. Natural bubble fields from breaking waves in littoral regions have a profound effect on performance of sonar systems; while the wakes of ships have a debilitating impact on the effectiveness of anti-torpedo torpedo defense systems. This research investigates the feasibility of using acoustic tomography as a suitable method to determine physical properties of bubble fields (e.g., attenuation and bubble size distribution).

OBJECTIVES

The current research's scientific objectives seek to establish methods to determine physical properties of bubbly water from *in situ* acoustic measurements. Currently, acoustic tomography is used to constructs images of the attenuation such that the spatial dependence and the magnitude of the attenuation can be estimated.

APPROACH

Rouseff et al.[5] have implemented an acoustic tomography algorithm to invert measured amplitude data to determine the attenuation within a region of bubbly water. They have applied the algorithm to only a portion of the data obtained during the "Delta Frame'' experiment conducted at the Scripps Pier facility. Data run 6 occurred during an otherwise quiescent period and provides a baseline for the background while data runs 5 and 7 occurred during significant wave breaking and rip current activity. Of particular interest is data run 5 because it coincided with experiments of other researchers, which provide independent measurements of the bubble field . The proposed work for FY00 has three components. First, the tomographic analysis initiated by Rouseff et al. on attenuation data from the Delta Frame experiment will be extended to other data runs. Second, the algorithm for the tomographic

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reconstruction of attenuation will be modified to produce an image of the spatial variation in sound speed. While the attenuation algorithm requires amplitude information of the received signals, the sound speed algorithm uses the time-of-flight of an acoustic pulse from the source to receive. Proper time-of-flight estimation for a pulse requires careful analysis because of the dispersive nature of a bubbly medium. The final component of the FY00 effort initiates the development of a method to invert a measured sound speed and attenuation to determine physical characteristics of the bubble field such as a bubble size distribution. The wave propagation model for bubbly medium given by Commander and Prosperetti[1] may provide the foundation for this inversion algorithm.

WORK COMPLETED

Three components of the proposed work were completed. First, raw acoustic data from the "Delta Frame'' experiment conducted at the Scripps Pier facility by Caruthers and others from NRL-SSC was obtained. Nearly, four and hours of data were available from Runs 5, 6, and 7. The first component culminated with the development of algorithms to extract sets of acoustic data and determine the quality of that data. The second component performed a spectral analysis of the data to quantify the attenuation over the 16 acoustic rays in the tomographic measurement. Although this analysis is different from that performed by Caruthers et al.,[3] it confirmed their results. The final, and perhaps most significant, component completed is the development of an effective medium theory that correctly accounts for multiple scattering. The details of theory are reported elsewhere; the results are summarized below.

RESULTS

The most significant result in the first year of this program is the inclusion of the effects of multiple scattering into an effective medium theory for linear wave propagation in bubbly liquids. Commander and Prosperetti[1] established a set of equations for an effective wavenumber, k_m, which describes the acoustic properties of bubbly liquids, when the bubbles are treated as independent scatterers. Their results are available in Ref. 1 and a detailed analysis leading to a modified theory is given in Ref. 2. When multiple scattering is included, the effective wavenumber in a bubbly liquid for an incident acoustic field with angular frequency ω is

$$k_m^2 = k^2 + 4\pi\omega^2 + \int_0^\infty \frac{a\, n(a)\, da}{\omega_{0m}^2 - \omega^2 + i(b_{vm} + b_{tm} + b_{am})}, \tag{1}$$

$$\omega_{0m}^2 = \frac{1}{\rho_m a^2}\left[p_0 \Re(\Phi) - \frac{2\sigma}{a}\right], \quad b_{vm} = \frac{4\mu_m \omega}{\rho_m a^2}, \quad b_{tm} = \frac{p_0 \Im(\Phi)}{\rho_m a^2}, \quad b_{am} = \omega^2 k_m a, \tag{2}$$

where the subscript m indicates a property of the effective medium. Briefly, the wavenumber in pure liquid is k. The number of bubbles per unit volume with equilibrium radius between a and $a + da$ is $n(a)\, da$. The angular frequency at resonance of a bubble with equilibrium radius a is ω_{0m}. The density and dynamic viscosity of the effective fluid are ρ_m and μ_m; σ is the surface tension for an interface separating liquid from the gas within a bubble. The undisturbed pressure within the bubble is p_0. The complex-valued function Φ is determined from consideration of the basic thermodynamics within the bubble. The viscous, thermal, and acoustic scattering loss mechanisms are given by b_{vm}, b_{tm}, and b_{am}, respectively. The results of Commander and Prosperetti can be obtained by dropping the m subscript everywhere in (2) and on the right hand side of (1).

Comparisons of Commander and Prosperetti's results with those in (1) and (2) show that multiple scattering effects become important at void fractions greater than 0.0001 (see Ref. 2). The void fraction in littoral regions, near the surface in blue water, and in the wakes of ships can easily exceed 0.01. The key feature of (1) and (2) is that attenuations can exceed 100 dB/cm and phase velocities approach 10^7 m/s.

IMPACT/APPLICATIONS

The current research and results have severe implications for sonar systems operating in bubbly water. The bubble size distribution in mature bubble clouds spans a range of radii from approximately 30 to 150 microns with the peak in the distribution occurring near 80 micron. The void fractions of these clouds are sufficiently large that multiple scattering must be considered. The theory outlined above shows that the attenuation of acoustic field with the bubbly water exceeds 100 dB/cm, and the resonance frequency of these bubbles span is roughly 20 to 100 kHz. Hence, the range of a sonar operating in this frequency regime will be severely impacted.

TRANSITIONS

Frank Henyey of APL-UW has compared the results of computations based on (1) and (2) to his recent work with the multiple scattering series.[4] Ronald Roy, who is currently making impedance tub measurements of bubbly liquids to determine the attenuation and phase velocity, has been given access to Ref. 2.

RELATED PROJECTS

ONR recently sponsored a Bubble workshop (Boston University, Spring 2000) to define basic research areas that need further study. Several initiatives were identified including a follow on acoustic tomography experiment, which would potentially use a modified version of the NRL-SSC "Delta Frame" apparatus (i.e., more sources and receivers, different array geometries, and improved signal processing).

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